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The seismic cycle in southern California: Precursor or response?

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Abstract. The seismicity rate (M≥3.0) in southern California shows two cycles with periods of high activity (90 events/year), from 1945-1952 and 1969-1992, and lower activity (60-70 events /year) from 1952-1969 and 1992-present. Abrupt drops in the seismicity rate occur after the 1952 Kern County (M7.5) and the 1992 Landers (M7.3) earthquakes. The sudden increase in 1969 does not coincide with any major event but approximates the time needed to reaccumulate the seismic moment released in the 1952 earthquake. This temporal correlation with the preceding earthquake suggests that the seismic cycle (lower seismicity after a major earthquake and higher seismicity before the next major earthquake) should be interpreted as a response to the first earthquake rather than a precursor to the second. Southern California is now at a rate of seismicity as low as it experienced in the 1950s and 1960s.

Introduction

The concept of the *seismic cycle*, a recurring pattern of low seismicity after, and higher seismicity before the major earthquakes in a region, has been prevalent in seismology for many years [e.g., *Imamura*, 1937] and has been proposed for at least one cycle, in the Kuriles [*Fedotov*, 1968], California [*Ellsworth et al.*, 1981; *Reasenberg and Simpson*, 1992; *Sykes*, 1996], and Japan [*Mogi*, 1969; 1981; *Shimizaki*, 1978]. Some interpret it as a steady-state background level followed by an increase in seismicity as the stress in a region accumulates towards a great earthquake, sometimes estimating the time to the next earthquake from the time of the onset of the higher rate of seismicity [*Mogi*, 1981]. Others [*Ellsworth et al.*, 1981; *Harris and Simpson*, 1996] have suggested that the post-earthquake decrease may be the significant signal. The difference is more than semantic. If the post-earthquake decrease is the only significant signal, variations in seismicity are only responding to past activity. Conversely, if the significant signal is the precursory increase, we would have evidence that the preparatory process of large earthquakes is different from that of smaller earthquakes, a necessary requirement for earthquake prediction.

The catalog of southern California earthquakes is one of the most complete and consistent available, and includes two major (M>7) earthquakes. This study analyzes that catalog for evidence of a seismic cycle associated with these earthquakes. We apply statistical techniques to assess when significant changes in southern California seismicity have taken place. We document how the rate of earthquakes (excluding aftershocks) changes and the temporal and spatial correlation between the rate of seismicity and the occurrence of major earthquakes. With this, we evaluate possible physical causes of variations in seismicity.

Data and Analysis

We analyzed the earthquake catalog of the Southern California Seismographic Network (SCSN), a joint project of California Institute of Technology (Caltech) and U. S. Geological Survey (USGS), for evidence of a seismic cycle related to its two largest (M≥7) earthquakes. The SCSN has been in operation since the 1920s and the catalog is complete at magnitude 3 since 1932 [*Hileman et al.*, 1973] and magnitude 1.8 since 1981 [*Given et al.*, 1989]. Our study region, covered by the SCSN, extends from 32.5°N to 36.0°N latitude and from 115.5°W to 120.5°W longitude (Fig. 1).

Consistent magnitudes are essential to any evaluation of seismicity rates [e.g., *Habermann*, 1982; 1987]. *Hutton and Jones* [1993] redetermined the magnitudes of all M≥4.8 non-aftershocks in the SCSN catalog since 1932 using present techniques and rereading amplitudes from original records. They found that the present amplitude reading practice began in 1945 and that magnitudes determined with a computer algorithm, beginning in 1975, were systematically smaller than earlier magnitudes determined by hand by an average of 0.07 units. A project to redetermine magnitudes for all older earthquakes has begun but only a few years (1956-1959) are completed. These few years show the same decrease in average magnitude for all magnitudes, as expected, if the difference is the use of computer algorithm.

Because all earthquakes are affected, one cannot eliminate the problem by choosing a different magnitude threshold. Instead, we

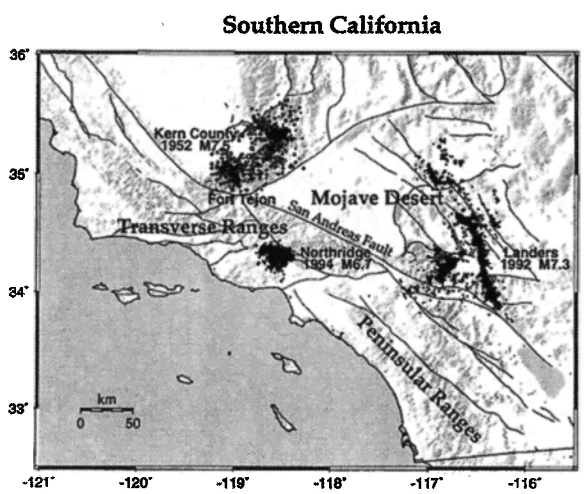

Figure 1. a) A map of southern California including the aftershocks to the 1952 Kern County and 1992 Landers earthquakes, defined by the clustering algorithm [*Reasenberg*, 1985].

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assume that all earthquakes before 1975 are 0.07 units smaller than their catalog value so that 70% of the magnitude 3.0 earthquakes before 1975 are actually magnitude 2.9 and not above our threshold. We test this assumption by comparing the 1956-1959 data in this corrected catalog with the computer-determined magnitudes recently completed for that time. The original declustered catalog has 307 events, the corrected catalog (original catalog with 70% of M3.0 events removed) has 276 events, and the new declustered catalog (computer magnitudes) has 278 events, demonstrating this correction is a reasonable approximation of the real catalog.

The largest variations in an earthquake catalog are aftershock sequences that obey Omori's Law, a known pattern of temporal decay [e.g., *Utsu*, 1969]. We remove aftershocks from the Caltech/USGS catalog with the algorithm of *Reasenberg* [1985] that does not impose arbitrary windows in space and time to define aftershocks, but rather searches the data itself to recognize earthquake clusters. By doing so, we do not deny the importance of aftershocks in strain release, but rather allow the opportunity to investigate other changes in seismicity rate. This process must be critically evaluated because inadequate declustering of aftershocks can cause spurious rate increases, and overclustering (removing background seismicity as aftershocks) will look like a decrease. To evaluate the effect of the declustering process on the results, we created three artificial catalogs for comparison. In the first, the clustering algorithm was modified to severely undercluster the catalog (leave aftershocks as independent events), in the second the algorithm overclusters (remove many background events), and in the third, the region of the Landers earthquake (with many aftershocks and many background events) was not included.

We evaluate changes in seismicity rate with the β-statistic, the difference between the rate during a subset of time minus the expected rate (assumed as the average rate for the whole time) normalized by the square root of the variance [*Matthews and Reasenberg*, 1988]. The average rate of M≥3.0 non-aftershock earthquakes in southern California is 79 events/year. We evaluate this statistic in all possible time intervals and search for the times

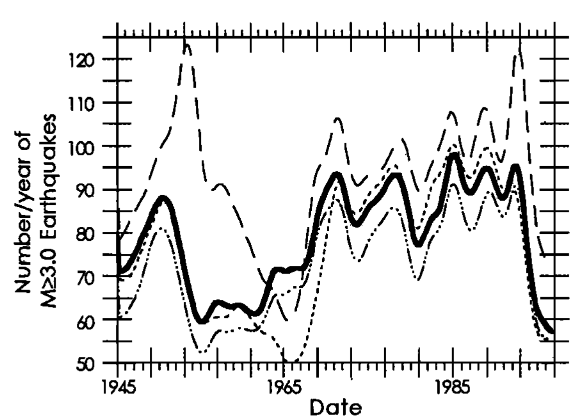

Figure 2. The smoothed rate of M≥3.0 earthquakes (number per year, excluding aftershocks) in southern California. Also shown are the number per year for an underclustered catalog (with some aftershocks mis-identified as independent events, see text: long dashed line), an overclustered catalog (with some independent events mis-identified as aftershocks, see text: short dashed line), and a catalog from which the area around the Landers aftershock zone and San Gorgonio Pass has been removed (dot and dashed line). These 3 artificial catalogs provide a bounds for the effect of the clustering algorithm on these results.

Table 1. Variations in Rates of Seismicity in Southern California

Time Period	Years	Rate of M≥3 Earthquake	β-statistic*
Jan 1945 — Jul 1952	7.6	80.8	0.60
Aug 1952—Jul 1969	17.4	67.2	-6.70
Aug 1969—Aug 1992	22.7	89.9	7.95
Sep 1992 —May 1996	3.75	62.1	-3.82
Jan. 1945 — May 1996	51.4	79	------

* The β-statistic is defined as the rate in this time minus the average of the full time normalized by the variance in the rate [Matthews and Reasenberg, 1988). The statistical significance for the β-statistic depends on the sampling interval. For this analysis, an absolute value of 3.72 is significant at the 90% confidence level, 3.93 for 95%, and 4.38 for 99% [Matthews and Reasenberg, 1988).

of maximum difference. The significance of a given value of the β-statistic decreases as the number of sampling points increases to account for the inherent bias implied by choosing an interval to examine [*Matthews and Reasenberg*, 1988].

We find three statistically significant changes in the rate of M≥3.0 seismicity in southern California (Fig. 2), a decrease in the rate beginning in August 1952, an increase around mid-1969 and a decrease in September 1992. The two decreases occur immediately after the two largest earthquakes in the southern California catalog, the July 21, 1952, Kern County earthquake [M_W 7.4; *Stein and Thatcher*, 1981], and the June 28, 1992, Landers earthquake [M_W7.3; *Sieh et al.*, 1993]. The increase does not coincide with any major earthquake. These changes define two periods of high seismicity and two periods of low seismicity (Table 1) for southern California. The same pattern is evident in all three artificial catalogs (Fig. 2). The underclustered catalog shows peaks immediately after both mainshocks as expected when aftershocks are inadequately recognized, but all show low seismicity in the 1950s and 1960s, high seismicity in the 1970s and 1980s and a significant quiescence since 1992.

The seismicity variations are not confined to the immediate epicentral areas of the Kern County and Landers earthquakes (Fig. 3). Both mainshocks reduce the seismicity in their immediate vicinity, as expected if strain affects the seismicity level. This effect is enhanced by the declustering process (what would have been background seismicity is clustered into the aftershock sequence). However, the catalog without the Landers region (Fig. 2) shows the same rate variations, so this is not the sole cause of the rate change. Much of the remaining variability in seismicity rate does not scale with the stress change in the mainshock but rather occurs within an east-striking band across the Transverse Ranges. The Kern County earthquake lowered the rate both near its fault in the western Transverse Ranges and in the eastern Ranges (Fig. 3a). This region experienced the largest increase when the seismicity rate rose in 1969 (Fig. 3b). The Landers earthquake also reduced the seismicity in the eastern Ranges and in much of southwestern California including the Peninsula Ranges and the Los Angeles area (Fig. 3c).

The seismicity rates are compared to the long-term average in Fig. 3 so that if a region is high in one time period, the region will look low in other times. This feature, along with the concentration of the variability around the Transverse Ranges leads to an appearance of mirroring between the time periods. The slight increase since Landers in the eastern Mojave involves few events and includes events that *Sieh et al.* [1993] considered aftershocks of the Landers event. The slight increase in the western Transverse Ranges in 1992-1996 includes the area where a significant change in the microseismicity (M≥1.8) was documented west of and after the 1994 Northridge earthquake [*Reasenberg*, 1995].

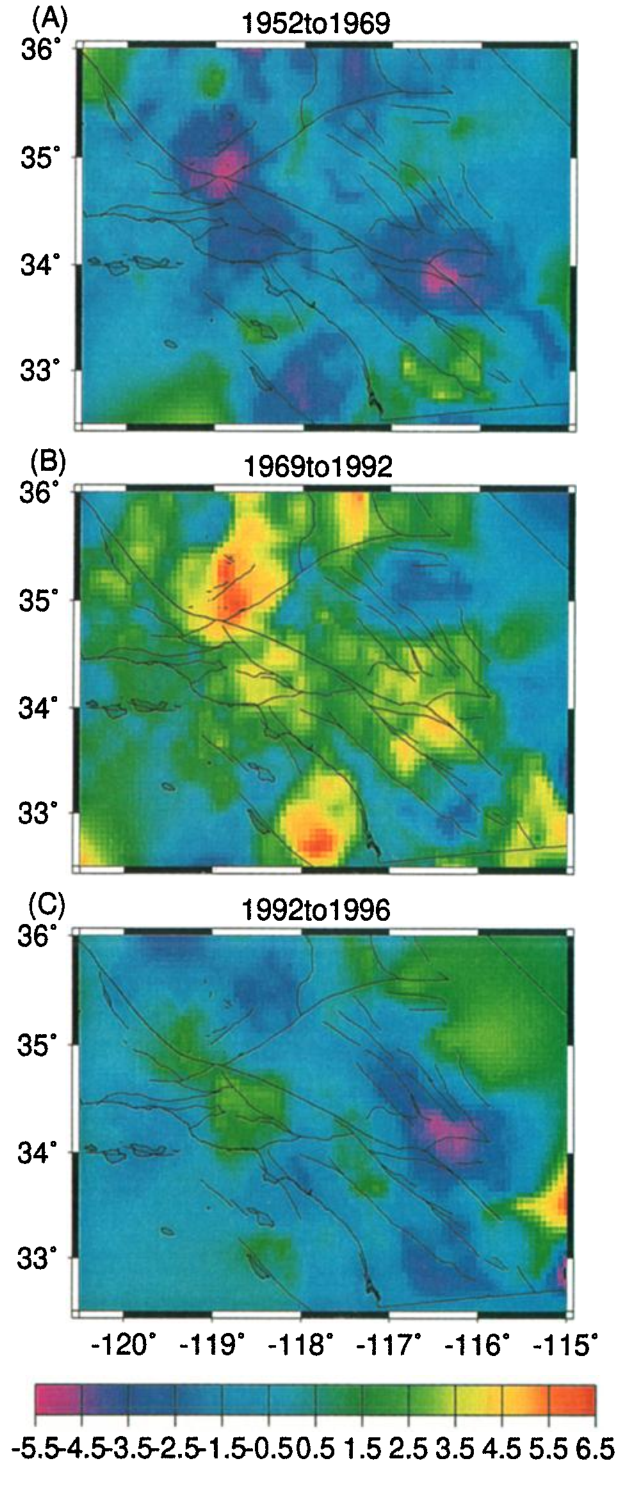

Figure 3. Values of the β-statistic, the number of earthquakes within each time period minus the expected number (from the rate from 1945 to 1996) divided by the variance, within overlapping 50-km -radius circles for a) August 1952 – June 1969; b) July 1969 – August 1992; and c) September 1992 – May 1996. The seismicity in each time period is compared to the average over the whole time in Figure 3 so a low β-statistic in a region can be a decrease in that time period or a higher rate in some other time. (For instance, the area offshore from San Diego has a low β-statistic in **a)** because it has a high rate after the 1986 Oceanside earthquake, whose aftershocks, 50 km from the nearest station are incompletely clustered. Thus, each time period is in part a mirror image of the other times.)

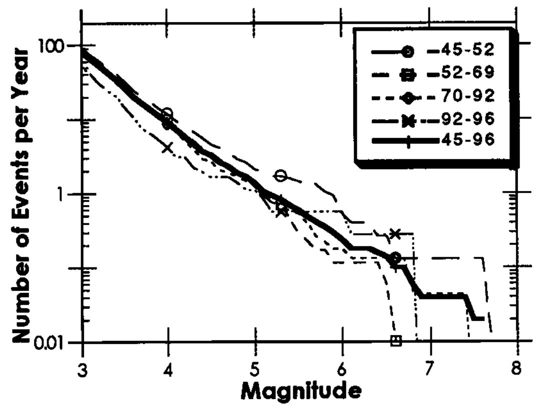

Figure 4. The cumulative rate of earthquakes (number per year) in southern California plotted against magnitude for January 1945 – July 1952, August 1952 – June 1969, July 1969 – August 1992, September 1992 – May 1996, and January 1945 – May 1996.

The period since September 1992 to present (July 1996) has the lowest rate of M≥3.0 earthquakes in the SCSN catalog but includes the 1994 Northridge earthquake (M_W6.7). The log-linear magnitude-frequency relationship for earthquakes [*Gutenberg and Richter*, 1954] predicts that on average, for every large event, many small ones will occur. The magnitude-frequency distribution of the declustered SCSN catalog (Fig. 4) shows a linear relationship between the rate of M≥3.0 and M≥6.0 earthquakes when using the full 51 years but more variability in any of the shorter times. The slope of the curve (b-value) does not vary significantly between the different times even though the frequency distribution curve is distorted in the higher magnitudes in particularly short intervals.

Discussion

These results demonstrate a statistically significant change in the rate of seismicity in southern California, consistent with many previous reports of seismic cycle. Some previous studies assumed that increased seismicity before a large earthquake must be precursory to that events, implying a causal relationship, but this is not necessary. Large earthquakes relieve tectonic stress and remove energy from the system, through rock fracture, frictional heating, and seismic radiation. A cyclic seismicity pattern could be a decrease following each major earthquake with a later return to normal seismicity. *Harris and Simpson* [1996] demonstrated an approximately 50-year quiescence after the 1857 Fort Tejon earthquake and *Ellsworth et al.* [1981] pointed out that the only statistically significant variation in the seismic cycle around the 1906 earthquake was the decrease following that event.

Three aspects of the cycles observed here suggest they are a response to the first earthquake rather than a precursor to the second. First, the rate of seismicity does not increase toward the time of the major earthquake. Rather, the rate is constant from 1969 to 1992, implying a steady-state condition. Second, although a seismic cycle is evident in these data, neither the Kern County nor the Landers earthquake could be considered a plate boundary event. A tenet of the traditional seismic cycle hypothesis is that the tectonic stress in a region is controlled by the failure cycle of the controlling fault of that region, yet two earthquakes on very minor geologic structures produced significant changes in the seismicity of the type cited as evidence for a seismic cycle.

Third, the duration of the lowered seismicity roughly corresponds with the moment of the preceding earthquake. The moment of the Kern County has been estimated at 1.2 x 10^{20} N-m [*Stein and Thatcher*, 1981] – 2.0 x 10^{20} N-m [*Hanks et al.*, 1975] and reduced the seismicity for 17 years. The 1857 Fort Tejon earthquake is estimated to be about 3-4 times larger [M_0=5.3–8 x 10^{20} N-m; *Sieh*, 1978] and reduced the rate of large earthquakes for about 50 years [*Harris and Simpson*, 1996]. The accumulation of seismic moment in southern California has been estimated from plate motions at 9.3 x 10^{18} N-m/ yr [*Working Group on California Earthquake Probabilities*, 1995]. The moment released in the Kern County earthquake would re-accumulate in 12-21 years, and the Fort Tejon moment in 55-85 years.

If this ratio holds for the Landers earthquake, its 0.9–1 x 10^{20} N-m moment [*Sieh et al.*, 1993] should produce a quiescence similar to or shorter than that after the Kern County event. Thus, sometime in the next decade, the rate of M≥3 earthquakes should return to its higher level of about 90 events per year. A return to a higher rate around 2002 to 2007 would support this hypothesis that the seismic cycle is a response to previous earthquakes. Southern California may very well produce large or major earthquakes during the quiescence—the rate of seismicity is reduced by one-third, not eliminated—but such major earthquakes would be more probable after the return to the higher rate of seismicity. Of the 12 M≥6 earthquakes in the last 5 decades, 9 or 75% have occurred in the 56% of the time with higher seismicity rate, but 3 did occur in the "quiet" times.

Although the rate of small earthquakes decreases in response to the two major earthquakes, this response is not a simple elastic response. This variability in rate of seismicity along the Transverse Ranges is consistent with the pattern of seismic release documented by *Press and Allen* [1995], who showed that thrust, oblique-slip, left-lateral, and other faults have been most active for the past two decades. They proposed a change in direction of the plate motion as the cause of this change. It may be that the moment release in the large earthquakes causes realignments of the fault blocks and microplate motions, not well explained by the elastic response of a half-space. The Transverse Ranges, next to the Big Bend of the San Andreas fault, may be more responsive to seismic moment release and the accompanying minor realignments of the plate motion. This is similar to the "seismic knots" of *Sykes and Seeber* [1985] but does not require that these regions be stronger than other parts of the plate boundary.

A true precursor, if found, would imply that 1) something happens in the crust before an earthquake can begin; and 2) that something is different for big earthquakes than for small events. The analysis presented here, however, suggests a non-precursory model of the seismic cycle. Plate motion produces a long-term accumulation of seismic moment. When a large earthquake removes energy from the system, the seismicity rate decreases until the moment has reaccumulated. At the higher, normal rate, earthquakes are more common and a rupture that propagates into another major event is more probable. This pattern can continually repeat with no precursory relationship between the seismicity rate and future events.

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